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14. ABSTRACT

A combination of theoretical, laboratory, and observational work was accomplished in order to study the dynamics of a western boundary current leaping across the strait with an emphasis on existence of multiple flow patterns and predictability. Earlier theoretical predictions were confirmed in a context of the Kuroshio in Luzon Strait using analysis of historical hydrographic data, results from the NLOM and NPACNFS numerical models. The efficient characterization of the intrusion in terms of subsurface temperature anomaly was analyzed. Strong correlations were found between the penetrations, the winter monsoon system and the Kuroshio transport fluctuations on the decadal, interannual, and seasonal scales.

15. SUBJECT TERMS

Kuroshio Penetrations, South China Sea, boundary current, predictability, Luzon Strait, winter monsoon system

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Kuroshio Penetrations into the South China Sea: Analysis of the Dynamics and Predictability

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LONG-TERM GOALS

Our ultimate goals are to understand the dynamics of the Kuroshio penetrations into the South China Sea and to develop a model of its predictability on interannual and seasonal time scales.

OBJECTIVES

Our objectives are:
1. To identify the main dynamical mechanism responsible for the Kuroshio penetrations into the South China Sea as a loop current,
2. To study the relationship between the loop current penetrations and external factors such as transport and speed of the Kuroshio outside the Luzon Strait, wind stress, and also velocities induced by excited basin Rossby modes.
3. To search for evidence of multiple quasi-steady circulation states and hysteresis in the loop current evolution, which will lay a basis for a predictability model of the loop current penetrations on seasonal and interannual time scales using a dynamical system approach.

APPROACH

Our hypothesis is that the Kuroshio usually leaps across the Luzon Strait; however, during periods when its strength is substantially reduced, it may penetrate into the South China Sea due to the beta effect (Sheremet, 2001). More importantly the flow can be in multiple quasi-steady states and the transition between them involves a hysteresis (dependence on prior evolution). We have been testing this hypothesis with a combination of (1) a theoretical analysis of the flow dynamics in the Luzon Strait, (2) an analysis of historical observations of the Kuroshio, and (3) an analysis of the output in the North Pacific Ocean Nowcast/Forecast System (NPACNFS) and Navy Layered Ocean Model (NLOM) developed at the Naval Research Laboratory at Stennis Space Center, focusing on the area near the Luzon Strait and on the northern part of the South China Sea.

TASKS COMPLETED

We analyzed the current measurements (Shipboard ADCP and moored array) collected in Luzon Strait (Tang, 2002) and compared them with the prediction of our theoretical model (Sheremet, 2001). We looked at historical data on the Kuroshio penetrations into the South China Sea, the results of the past numerical simulations conducted by Metzger and Hurlburt (2001) using the Navy Layered Ocean Model (NLOM) and connected them with the estimates of the circulation strength in the Northern Pacific subtropical gyre inferred from the Kuroshio Path Index (Qui and Miao, 2000; and Qui, *pers. comm.*). We also analyzed the output of NPACNFS provided by D. Ko. We worked with 5-day averaged flow fields looking for the evidence of connections between the various dynamical processes occurring in the North Pacific basin, the Kuroshio strength east off Luzon and Taiwan, and loop current penetrations into the South China Sea. The seasonal variation of the Kuroshio penetrations into the South China Sea was analyzed based on the outputs of the NPACNFS model covering the time from 1999 to present, and of the NLOM model running in a hindcast mode from 1993 through 2000, which assimilate satellite information. We looked for the relationships between intrusions and external forcings such as the wind stress obtained from the ECMWF reanalysis covering a period from 1957 through 2002, the Kuroshio transport and dynamic height fluctuations outside the Luzon Strait. We used the observational data from the NODC archive (T, S, dynamic height), High Resolution XBT network (HRX, Gilson and Roemmich, 2002), and drifters (Centurioni *et al.,* 2003). The findings were compared with the prediction of our theoretical model (Sheremet, 2001) and with a more advanced model incorporating realistic coastline and stratification. To suppress short time scale variability we employed the method of relaxation to a running mean (Sheremet, 2002). We find the drifter observations (Centurioni *et al.,* 2004) to be in very good agreement with our seasonal timing based on historic hydrographic measurements, wind stress variability and the output of the numerical models.

We analyzed possible connection between the Kuroshio fluctuations in Luzon Strait and the excitation of quasigeostrophic basin modes in the South China Sea by solving an eigenoscillation problem for a semi-enclosed sea. We also worked with T. Duda on the effect of the Kuroshio penetrations on propagation of internal solitons generated in the Luzon Strait and observed during ASIAEX.

We also conducted laboratory modeling of a western boundary current leaping across a gap in order to validate our previous numerical findings about multiple flow paths and hysteresis in evolution. The novel approach in these experiments was in using a model of sink-source flow driving through sponges which allows to generate a western boundary current with prescribed distribution of potential vorticity in the source region, in particular, Toole *et al.* (1990) observed that the distribution of potential vorticity is essentially uniform at the origin of Kuroshio. The experiments were conducted for the range of nondimensional parameters similar to the geophysical ones and showed a good qualitative agreement with observed flow patterns in Luzon Strait based on ten years of ADCP measurements and with numerical simulations using the NLOM nowcast/forecast system.

Field observations were conducted in Luzon Strait from RV HaeYang 2000 (NORI, Korea) in October, 2004 during the winter monsoon season when the Kuroshio penetration was present. The ADCP,CTD, drifter and other relevant data were collected and analyzed with the emphasis on the structure of the inflow.

RESULTS

The major results of this research are following. On the decadal time scale there appears a correlation between the Kuroshio penetration and the strength of wind forcing in the subtropical Pacific Ocean (Sheremet, 2003). Analysis of the hystorical hydrographic data shows that on the seasonal time scales the most evident signal of the intrusions occurs at depth around 150m just west of Taiwan during winter months, Nov-Feb, (Figure 1) and it is out of phase with the temperature fluctuations in the Pacific. Such intrusions are clearly related to the winter monsoon system. They follow the minimum in the total transport of the Kuroshio in late summer. Less frequently intrusions occur also during spring-summer season, however, they follow the different more southern pathway into the South China Sea (Figure 2). This is caused by the change in the mean surface circulation in the South China Sea correlated with the transition between the winter and summer monsoons. The measure of intrusion integrated over a year starting in July is highly correlated with the averaged intensity of the winter monsoon system suggesting predictability on interannual time scales.

Solving the eigenoscillation problem for long period quasigeostrophic modes in the South China using the realistic bathymetry ETOPO5 revealed that the lowest mode is concentrated in the northeast corner of the South China Sea near Luzon Strait because of the combined planetary and topographic beta effects. Its spatial pattern is shown in Figure 4 (left panel). The period of the mode is about 13 days. The moored current measurements in Luzon Strait (data provided by D. Tang, Nat. Taiwan Univ.) show remarkable peak in energy at the same frequency (Figure 4 right panel) indicating possible resonance between the Kuroshio fluctuations in Luzon Strait, spring-neap tidal cycle, and excitation of basin oscillations.

The laboratory modeling (Figure 5) of a western boundary current leaping across a gap (Sheremet and Kuehl, 2005) provided an independent proof of the existence of multiple flow paths and hysteresis in evolution allowed to validate our previous numerical findings.

The field observations of the Kuroshio intrusion in October, 2004, during the winter monsoon showed that the westward current flowing through Luzon Strait is broad and strong with speeds about 1 m/s (Figure 6, 7) concentrated in the upper 200m. The velocity profile has a very distinct cusp at the maximum characteristic of the front separating two different water masses (Figure 8). The data also showed the development of shadow zones in the wave of small islands present in the strait.

IMPACT FOR SCIENCE

Our results have a fundamental nature: they offer the first geophysical example where the combination of the beta-effect and inertia produces multiple patterns of flow in the context of strait dynamics. Being generic they can be applied to other areas in the world ocean where the current has to negotiate a strait or a gap in the boundary such as in the Gulf of Mexico, or in the Gulf of Maine.

The results of the laboratory and accompanying numerical solutions offer an idealized test case for realistic numerical prediction systems in terms of validating mechanisms and schemes of flow separation and reattachement in the strait.

The results of this research have been published and submitted for publication in a number of peer-revied journals, presented at many national and international conferences: the European Geophysical Union General Assembly (Sheremet, 2003a), the American Meteorological Society Meeting (Sheremet, 2003b), and at a number of seminars, in particular, at the Scripps Inst. Oceanography, WHOI, MIT, Oregon State Univ, UCLA, National Sun Yatsen University (Taiwan).

RELATIONSHIP TO OTHER PROGRAMS

The PI actively communicated the results with Glen Gawarkiewicz, Tim Duda (WHOI), and D. Ko (NRL, Stennis Space Center) to help interpret observations during ASIAEX and to diagnose the output of the NPACNFS. We also discussed the results with John Gilson and Dean Roemmich (maintaining HRX network) as well as with Luca Centurioni and Peter Niiler (Scripps) conducting a drifter release project (supported by ONR) around the Luzon Strait.

The PI also studied a similar phenomenon of a boundary current leaping across the gap in the context of a shelf-break current in the Georges Bank area. It was found that the loop current penetrations are caused by weakening of the shelf-break front as expressed by its density difference (Cho *et al.*, 2002).

NLIWI. The PI actively works with Peter Niiler and Luca Centurioni (Scripps) funded by the project "Internal Wave Velocity Profiles from Wind Drifters in SCS" under the NLIWI DRI. The PI along with Luca Centurioni took part in the field work during the drifter internal wave array deployment from Ocean Researcher 2 and 3 in May, 2005 as a part of VANS/WISE experiment. It is planned that the PI will participate in the main NLIWI experiment in May 2007 and will assist Centurioni in launching and recovering of drifter buoys. However, the main responsibility of the PI, as before, will be in collecting, processing, and analyzing of the shipboard hydrographic and ADCP data relevant for characterization of the background circulation

JIMO NORI cruises. Peter Niiler ahas established contacts with Korean researchers from NORI. As a part of JIMO (Joint Institute for Marine Observations) program five cruses have been planned to Luzon Strait in Octobers of 2004-2008 in order to study the structure of the Kuroshio inflow based on hydrographic, ADCP, and drifter data. The PI actively participates in this program as well, he took part in the 2004 cruise and plans to participate in 2006 cruise. The PI will be responsible for analyzing the hydrographic and ADCP data and providing the synthesis of 2004, 2005, and 2006 cruises. During each cruise five crossings of the Kuroshio front are planned which would provide very accurate description of the velocity field structure in relationship with the surface expression of the front. During these cruises drifters with drogues at 15m and 150m will be also released enhancing the dynamical picture with the lagrangian view.

The PI also actively collaborates with David Farmer (URI) who is funded to test PIES (inverted echosounders) instruments for detection of solitons near Luzon Strait. The information on the sound velocity variability collected by repeated CTD observations aboard the R/V Ocean Researcher 3 and 2 in May 2005 was provided for programming of the PIES for July, 2005 deployment. Information relevant to Kuroshio Loop Current will be exchanged with his group.

Also Watts, Donohue, Wimbush (URI) proposed to put an array of PIES around Luzon Strait specifically for characterization of the loop current position. The PI extensively exchanged information with them regarding design and optimal placement of the array and predictability of Kuroshio Intrusions.

FIGURES

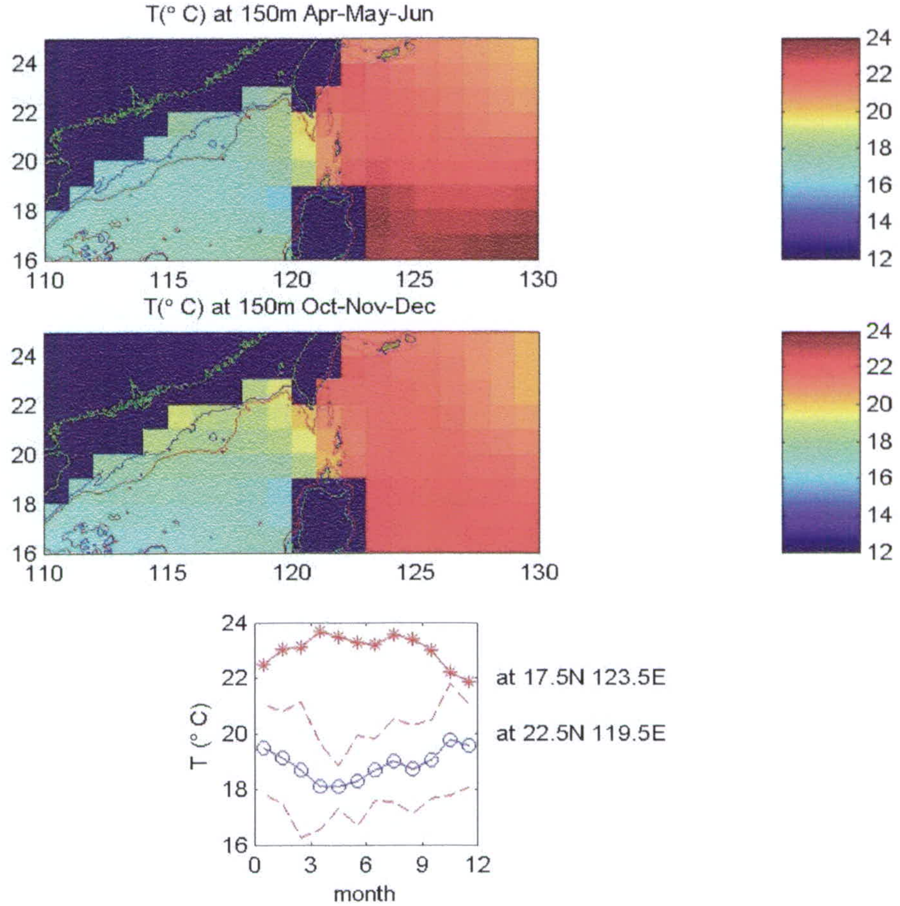


Figure 1: The distribution of the seasonally averaged temperature at 150m depth around the Luzon Strait: the spring season Apr-May-Jun (upper panel); the fall season Oct-Nov-Dec (middle panel). The coastline, 200m and 1000m bathymetric contours are shown. The seasonal variation of temperature at 150m (lower panel) averaged over a 1x1 degree square at two characteristic locations: at 17.5N 123.5E outside the South China Sea (red curve and stars) and at 22.5N 119.5E inside the South China Sea just west of Taiwan (blue curve and circles). Dashed curves indicate the standard deviation. The data are from the World Ocean Atlas 2001, National Oceanographic Data Center.

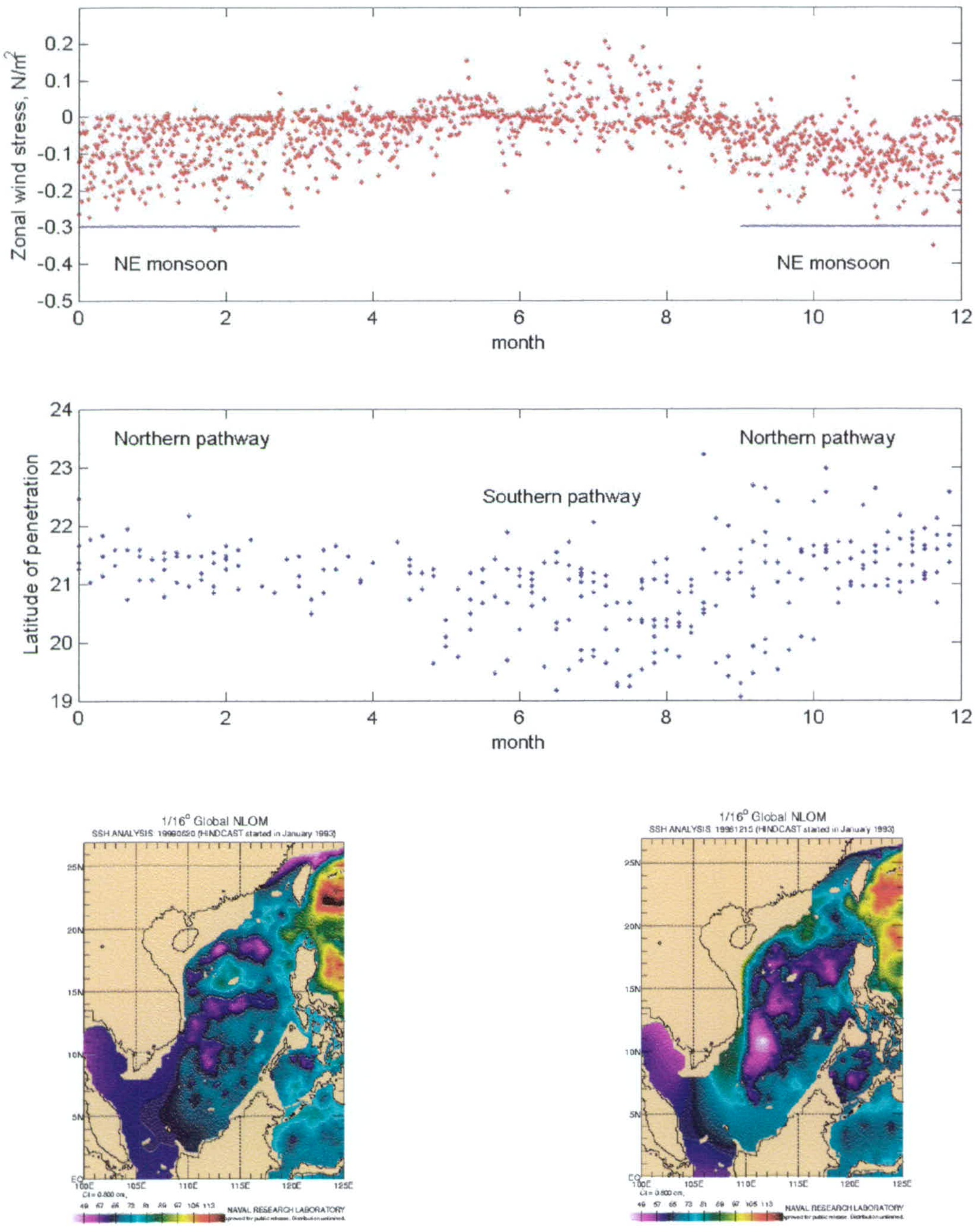


Figure 2: The ECMWF reanalysis zonal wind stress (during 1994-2000) at a representative location in the South China Sea 20N 120E (same as in Farris and Wimbush, 1996) indicating the seasonal variation of the northeast monsoon (upper panel) . The seasonal variation of the Kuroshio penetrating loop current latitude indicating the two different (southern and northern) pathways of penetration (middle panel). Examples of the flow patterns corresponding to the southern pathway (1999/06/20, lower left) and northern pathway (1998/12/15, lower right). The results are based on an analysis of the NLOM SSH data during the hindcast run for the period 1993-2000.

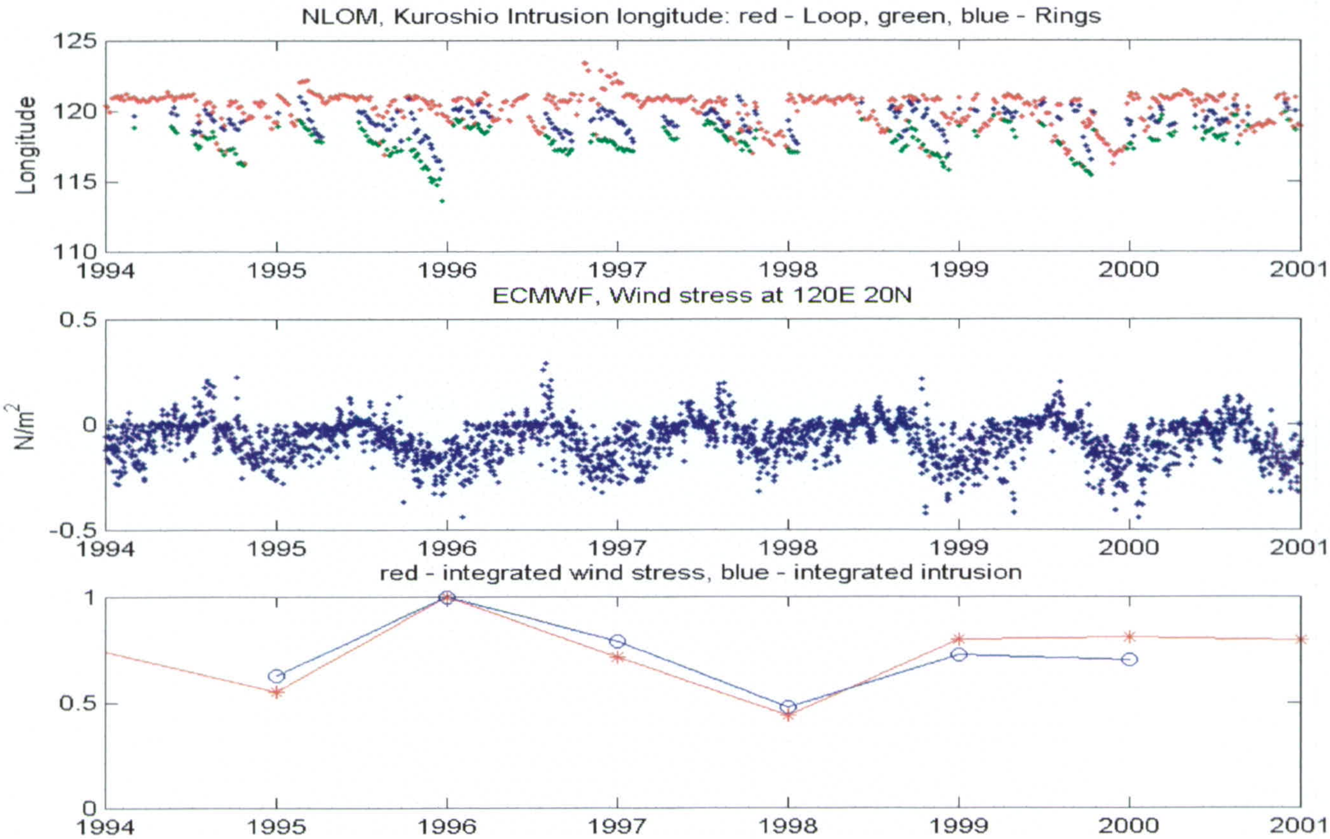


Figure 3: The eastward zonal penetrations of the Kuroshio loop current and rings according to the NLOM (upper panel). The ECMWF reanalysis zonal wind stress (during 1994-2000) at a representative location in the South China Sea 20N 120E (same as in Farris and Wimbush, 1996) indicating the seasonal variation of the northeast monsoon (middle panel). The comparison between the annually averaged penetration and averaged wind stress shows a significant interannual correlation (lower panel).

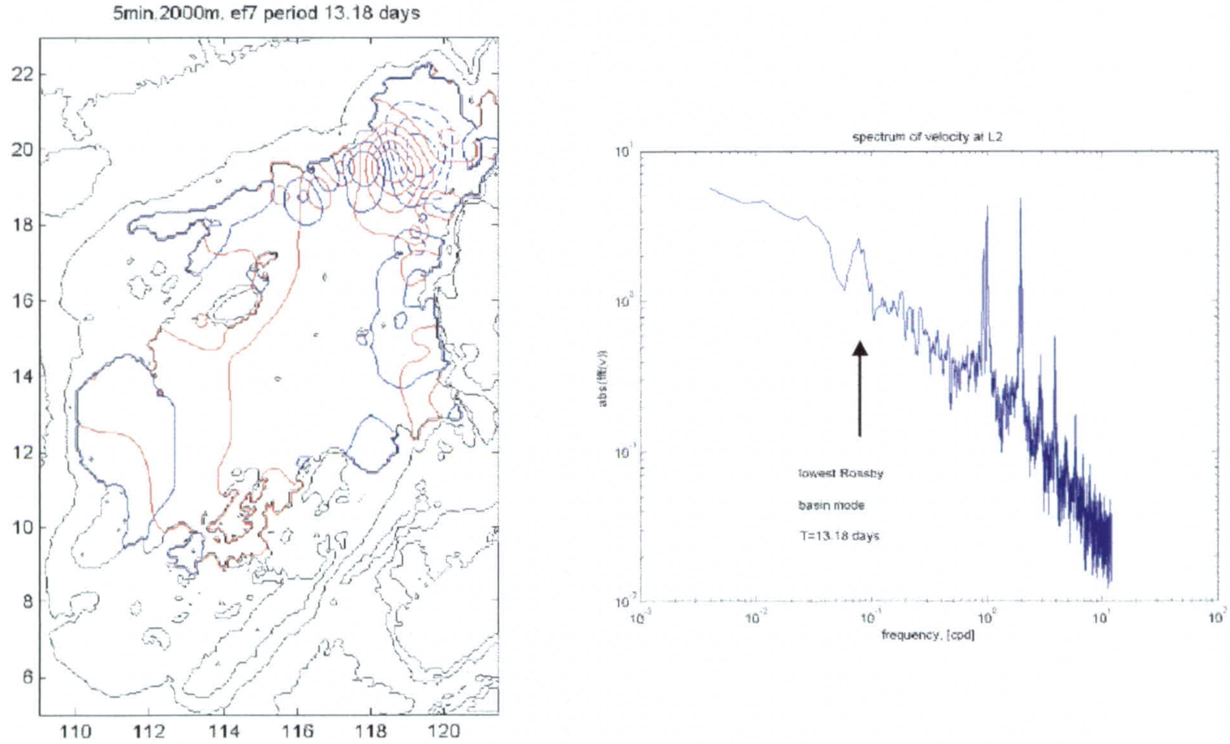


Figure 4: The pattern of the lowest quasigeostrophic eigenmode in the South China Sea (left panel) computed using the realistic bathymetry ETOPO5. The red contours indicate the real part and the blue ones indicate the imaginary part of the eigenfunction. The spectrum of the nearsurface velocity at the mooring in Luzon Strate (right panel) shows significant peak at the period of about 13 days same as the period of the eigenoscillation indicating a possible resonance between the Kuroshio fluctuations and the basin oscillations.

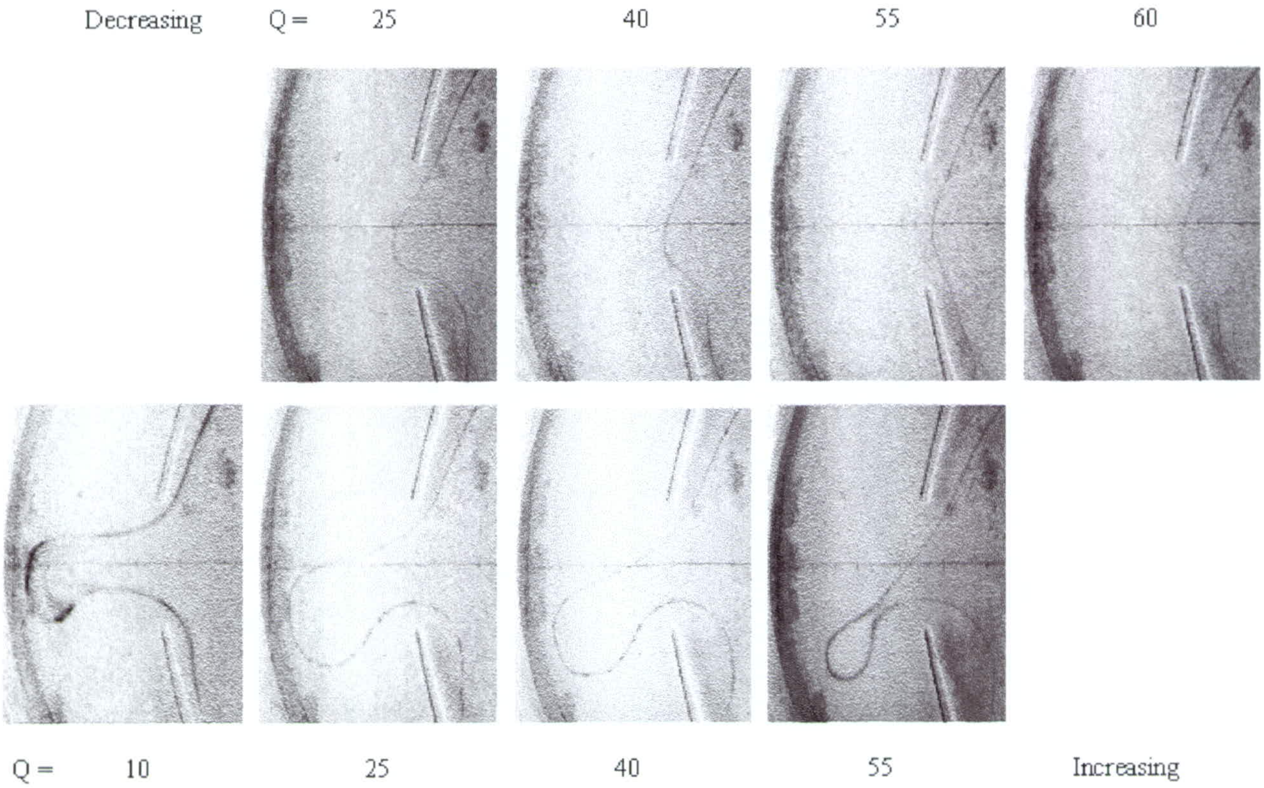
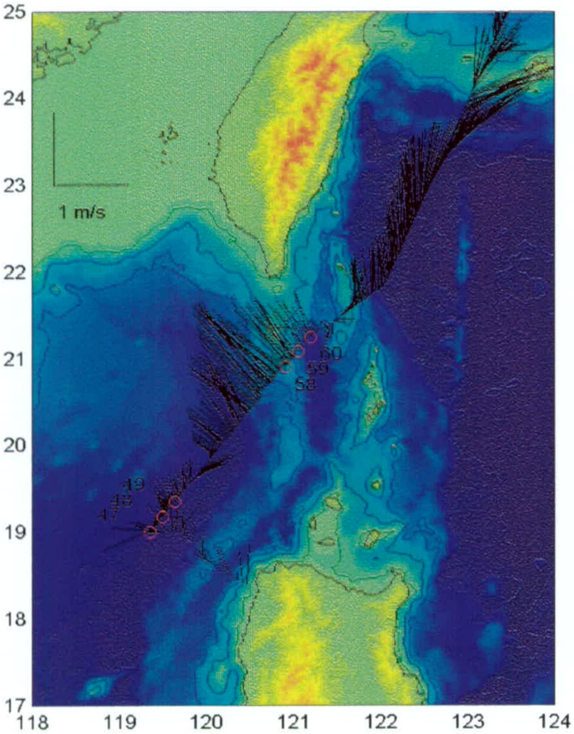


Figure 5: Steady flow patterns from the laboratory experiments in a rotating tank illustrating the hysteresis as the pumping rate Q is varied between 0 and 60 cm^3/s. Only a portion of the tank focused on the gap is shown. A stream line passing through the core of the boundary current is visualized by dye release. The flow is from top to bottom of the figure. Within the range $23 < Q < 55$ cm^3/s two different steady solutions are possible. The lower panel shows the experiments with increasing flow rate while the upper panel -- with decreasing flow rate (from Sheremet and Kuehl, 2005).



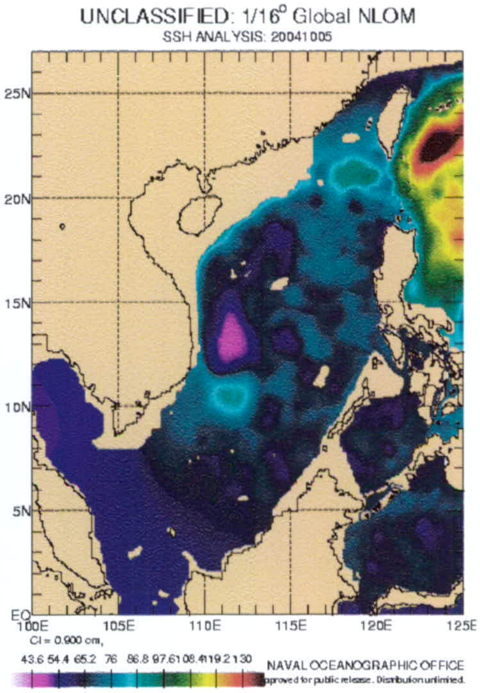


Figure 6. The near surface velocity during a transect across Luzon Strait on October 4-5, 2004. Data were collected by the RDI-ADCP system aboard R/V HaeYang 2000, NORI, Korea as a part of JIMO observational program. The circles indicate two groups of CTD stations inside the South China Sea water mass (47, 48, 49) and inside the Kuroshio water mass (58, 59, 60).

Figure 7. The Sea Surface Height field according to the NLOM on October 5, 2004 at the time of the hydrographic survey.

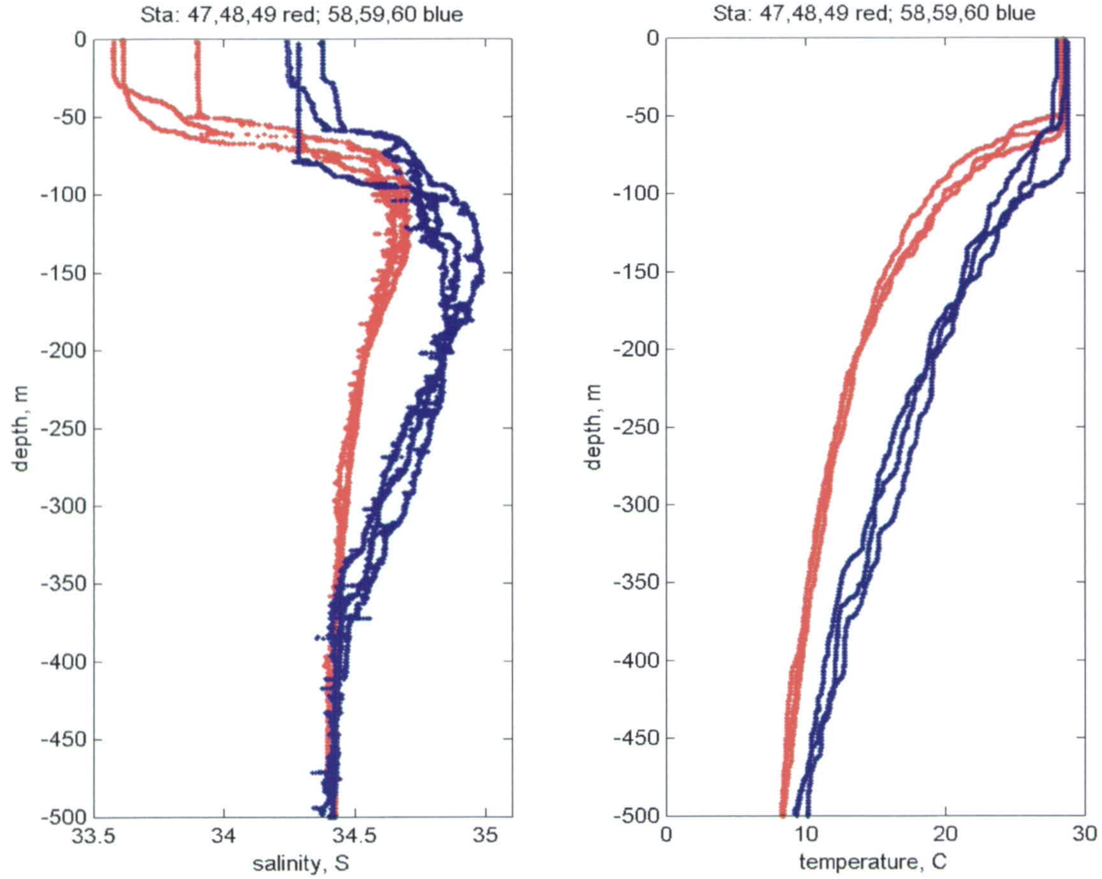


Figure 8. Contrast between two groups of hydrographic stations across the front of the Kuroshio intrusion: Red color indicates stations (47,48,49) south of the front, inside the South China Sea water mass; blue color indicates stations (58,59,60) north of the front, inside the Kuroshio water mass.

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